Rögen Moraine as a Transitional Bedform in an Erosional Subglacial System

Robert Kryzer
Swenson College of Science and Engineering
University of Minnesota Duluth
Kryz0012@d.umn.edu

Abstract: *Ribbed (Rögen) moraine in northeastern Minnesota associated with the Rainy Lobe of the Laurentide Ice Sheet is extensively distributed at transition of scoured Canadian Shield bedrock and thick drumlinized till and is associated with eskers. This setting suggests a strongly extensional glaciological setting as the ice transitions from bedrock to thick unconsolidated sediment. As part of our investigation of ribbed moraine formation simple glaciological modeling is used to conceptualize the ice flow regime and ground-penetrating radar (GPR) isused to study internal structure of the forms. Our numerical flow model used a specified accumulation pattern and basal shear stress distribution to calculate the balance velocity and assess increasing ice velocity across the bedrock-till transition where ribbed moraines occur. GPR profiles were collected parallel to ice flow and multiple profiles on one form were used for 3-dimensional analysis. Modeling suggests that the velocity increase across the transition is likely no greater than 100%. GPR reveals that about half of the ribbed moraine forms have an imbricated structure on the stoss side that we interpret as depositional. We conclude that ribbed moraine in NE Minnesota formed in a net erosional environment. As the drumlinized till thinned, ribbed moraine became the stable bedform. We interpret the imbricate structures on the stoss side of the forms as local deposition of till suggesting that the forms were migrating upglacier. The association with eskers suggests that effective subglacial drainage enhances ribbed moraine formation.*

1. Introduction

Rögen (ribbed) moraine, initially described near Lake Rögen, Sweden (Hoppe,1959; Lundqvist, 1969), have been identified in Scandinavia,Canada, and parts of the US (Lundqvist, 1989; Hättestrand, 1997; Clark, 1999; Clark and Meehan, 2001; Dunlop and Clark, 2006) , and characteristically described by Hättestrand and Kleman (1999), and Dunlop and Clark (2006) and defined by Jan Lundqvist (1989). Rögen moraine are parallel ridges forming subglacially transverse to iceflow in the interior regions of icesheets, however the mechanism(s) of formation is(are) enigmatic. There has been considerable work in analyzing till fabric (Lundqvist, 1997; Sutinen et al., 2010), excavation of ridges (Fisher and Shaw, 1992; Möller, 2006), and remote sensing (Dunlop and Clark, 2006), which suggest a complex origin.

The two leading hypotheses in Rogen formation are: 1) The shear and stack theory, suggesting formation by shearing and stacking of till sheets or englacial material during compressive flow (Bouchard, 1989); and 2) The fracturing theory, which explains extensional ice flow results in deformation of soft material below an ice sheet and above a competent (hard) material, such as bedrock (Hättestrand, 1997; Hättestrand and Kleman, 1999). In both theories, a polygenetic sequence is possible or implied and, depending on specific hypothesis of formation, the internal composition and structure may or may not matter.

We suggest a once continuous till sheet existed under the Laurentide Ice Sheet (LIS) from the Hudson Bay Lowlands to the terminus (Larson, 2008). Deposition of a continuous till sheet during the growth phase of the ice sheet is followed by remobilization of subglacial till and transition to hard-bedded conditions in the interior of the ice sheet during the late stages of glaciation. The resulting transition from a scoured bedrock to an unconsolidated sediment substrate (hard to soft bedded conditions) represents a boundary between two different glaciological regimes: 1) An interior region with high basal shear stress, characterized by a relatively low sliding velocity, overlain by a relatively thick ice sheet; and 2) An ice marginal region with low basal shear stress, characterized by relatively high sliding velocity, overlain by a relatively thin ice sheet. The increase in sliding velocity at this boundary can be expected to increase the overall sediment flux and substrate erosion rate of the ice sheet.

The transition from bedrock (hard) substrate to unconsolidated sediment (soft) substrate formed during the last LIS is preserved in northeastern Minnesota. Here, extensive patches of Rögen moraine occur at the transition from scoured bedrock to drumlinized till (shown in Figure 1 and Figure 6). These Rögen moraine then also represent a transition from sediment limited to transport limited erosion in a subglacial system. The focus of this study is to characterize Minnesota's Rögen moraine and glacial bedform suite using LiDAR and illuminate the internal structure of Rögen moraine using Ground-Penetrating Radar.

2. Geologic Setting

The Arrowhead region of Minnesota was glaciated by the Rainy Lobe, an o_shoot of the Laurentide Ice Sheet, during the Last Glacial Maximum. Rögen moraine is found ~250km up glacier from the terminus. Upglacier of MN Rögen moraine is scoured bedrock of Canadian Shield. Downglacier of Minnesota ribbed moraine is increasingly thick, drumlinized till. Rainy lobe's till average grain size is 76% sand, 22% silt, and 2% clay, with textures ranging from sand to silty sand (Lehr, 2000).

3. Evolution of the Landscape

Consider an ice sheet on easily erodible soft sediment that promotes basal sliding and subglacial sediment deformation. Through glaciation cycles, erosion and advection of preglacial regolith and sediment reservoirs exposes hard bedded conditions restricting basal sliding and promoting thicker ice sheets that cover a smaller area. The removal of regolith beneath the LIS has been considered the cause of the transition from 40 ky to 100 ky glacial cycles found in the early Pleistocene to late Pleistocene glaciations (Roy, 2004). After establishing hard bedded conditions, the LIS continued to erode and mobilize isolated patches of unconsolidated sediment, as evident from isolated drumlins found on Minnesota's northern border (can be seen in Figure 1, underneath Absract text). Rögen moraine of northeastern Minnesota form extensively at this transition from hard bedded to soft bedded conditions and are thus records of the transition of high to low basal shear stresses and, perhaps independently, the transition from sediment limited to transport limit conditions. Near the toe of the LIS, the Rainy Lobe formed the Toimi Drumlins. Erosion of these drumlins due to the advancement of hard bedded conditions causes thinning of the till sheet. The result of thinned drumlins leads to Rögen moraine formation suggesting they become the stable bedform in an erosional subglacial environment.

4. Rögen as Transitional Bedforms

Northeastern Minnesota Rögen moraine form in and adjacent to the Toimi Drumlin field (TDF). While drumlinized glacial drift can be quite thick in the TDF, Rögen occur in relatively thin drift, within 80 km of scoured bedrock terrain but dominantly at the interface of hard bedded and soft bedded conditions. Their occurrence at a major glaciodynamic boundary indicates that Rögen moraine are an important record of sediment-ice sheet dynamics. The TDF is characterized by a network of cross-cutting drumlin-parallel eskers. Rögen moraine patches commonly occur in thin drift in close proximity to eskers, as parallel flanking zones. Esker paleoflow directions are generally parallel to the Rainy Lobe's flowline, and orthogonal to Rögen moraine (Figure 2 and 4). Cross cutting relationships in a Rögen field south of Hoyt Lakes, Minnesota show eskers and Rögen formed contemporaneously under the influence of a late, local ice flow direction, and are superimposed on drumlins formed during an earlier, regional ice flow direction (Figure 3). Observations show esker proximity promotes the transition of drumlinized till into Rögen. The association of Rögen with subglacial meltwater channels is a consequence of decreased pore water pressure adjacent to the channels. Decreased pressure, in turn, locally increases basal shear stress, generating the shear stress instability that triggers Rögen formation. However, the entire landscape is not Rögenized suggesting that here, in northern Minnesota, we are at the threshold of basal shear stresses involved in Rögen formation.

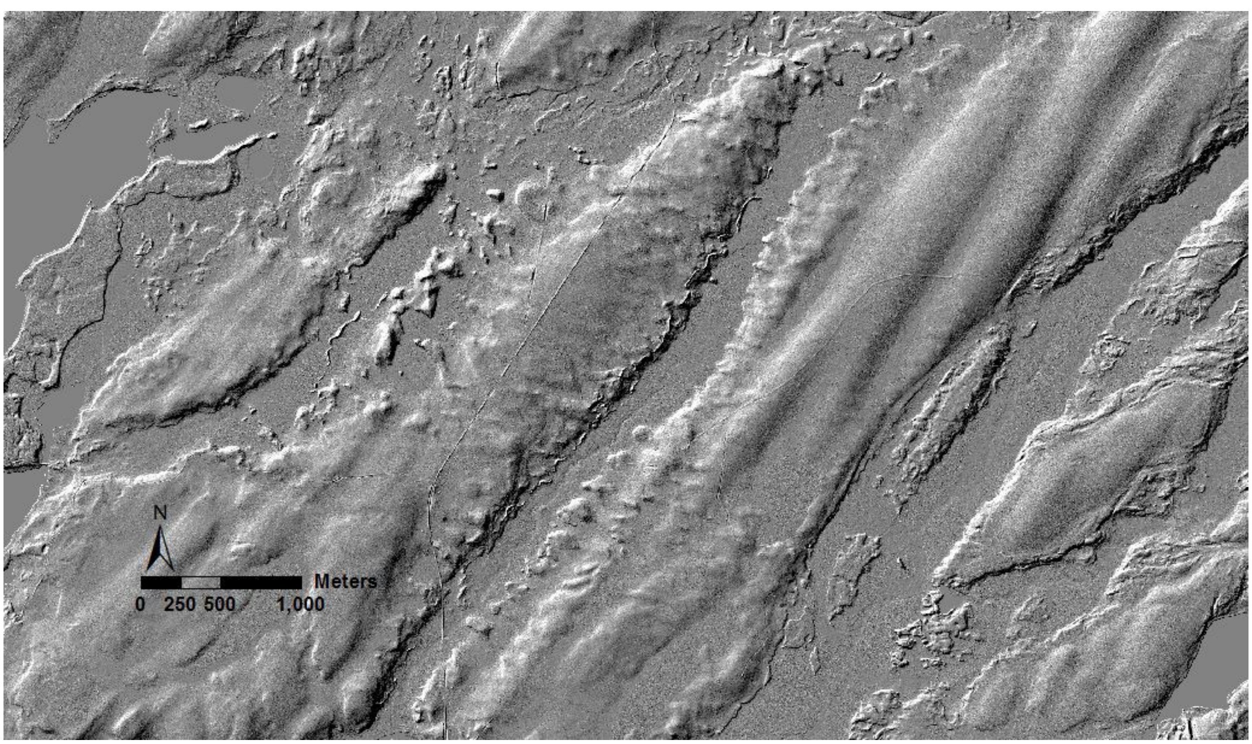

Figure 2 - LiDAR image showing Toimi Drumlins formed in a NE-SW regional _ow line being cross-cut by parallel eskers. Ribbed moraine are superimposed on flanking edges of the drumlins in the vicinity of these ekser. Local meltwater drainage reduces the pore water pressure resulting in increased basal shear stress. This observation that drumlinized till is undergoing reformation into Rögen in discrete areas of increased basal shear stress suggests that this area is near the basal shear stress threshold needed to trigger Rögen formation

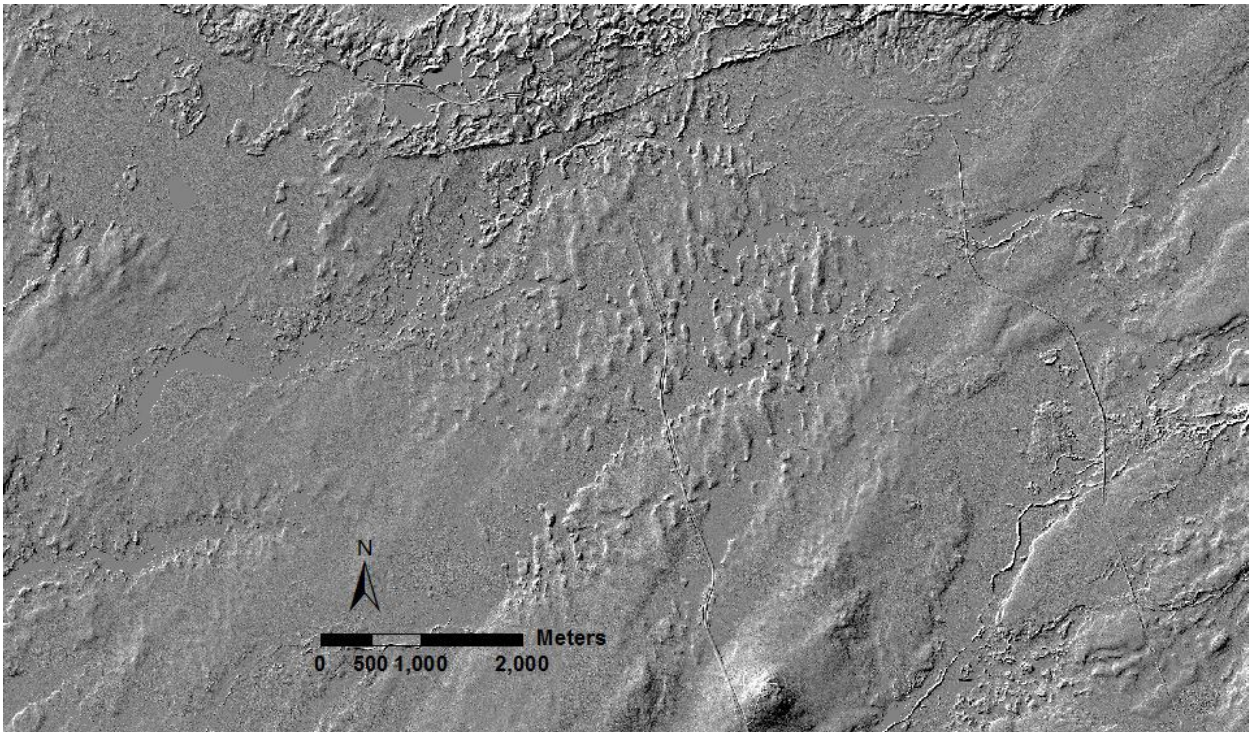

Figure 3 - LiDAR image showing superimposed Rögen moraine on Toimi Drumlins near Hoyt Lakes, MN. St. Louis County Highway 110 bisects the field. The Drumlins were formed in a NE-SW regional flowline. Rögen moraine formed transverse to a localized east-west flowline. Allignment of eskers perpendicular to Rögen means subglacial drainage established to this localized flowline and the eskers and Rögen formed contemporaneously. The increase in local basal shear stress due to meltwater drainage enhanced ribbed moraine formation.

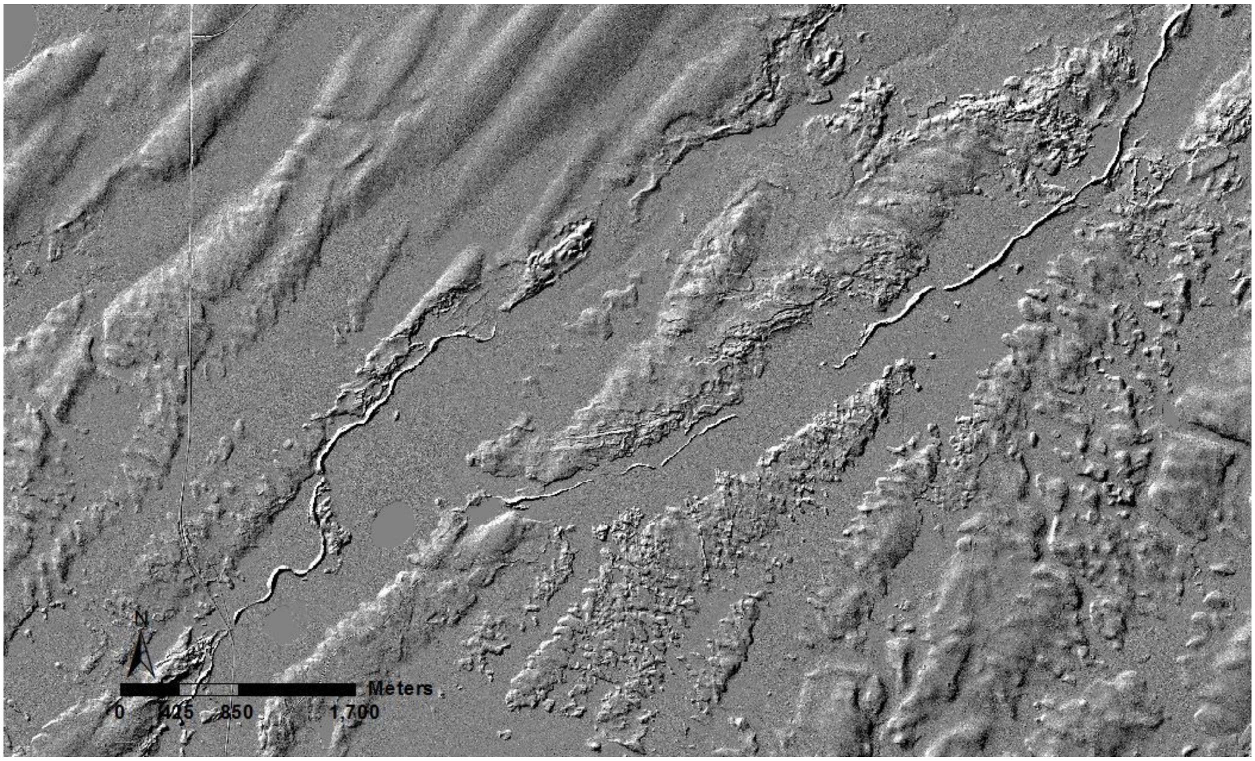

Figure 4 - LiDAR image of a portion of the Toimi Drumlin field cross-cut by eskers. Image shows drumlins with superimposed Rögen moraine. Enhanced drainage of englacial meltwater reduces the hydraulic pressure within the ice sheet and causes pronounced ribbed moraine formation.

5. Ground-penetrating Radar

Glaciotectonic structures within ribbed moraines have been reported by Fisher and Shaw (1992) during excavation of Newfoundland's Avalon Rögen moraines. They described imbricated up-glacier dipping structures within the ridges. Rather than excavating, we used ground penetrating radar (GPR) to image the interior structure of Rögen moraine. Transects were conducted using a Sensor and Software Pulse EKKO 100 with 50 Hz antennas. We used 1.5 meter spacing between the transmitter and receiver antennas with .5 meter step intervals. Subsurface velocities were calculated using a common-middle point analysis and found to be .118m ms¬-1.The scans were topography corrected using the elevations from LiDAR. Data interpretation was problematic in some cases due to hyperbolic reflectors, interpreted to be boulders. Two dimensional transects were collected across five (5) Rögen ridges. In addition, we conducted a 3-dimensional survey that is 60 meters by 7.5 meters on the stoss-side of a ribbed moraine. In the two dimensional surveys we interpreted the up-ice dipping reflectors as imbricated sediment packages. These up-ice dipping reflectors, when observed, are predominately located on the stoss side of the ridges. These observations are consistent with Fisher and Shaw's excavated observations (1992). We hypothesis these imbricated structures as collected packages of down ice advected sediment, suggesting the landform is propagating upglacier. The lack of dipping reflectors beyond the crest is considered to be due to the reworking of the sediment packages into subhorizontal, and possibly boudinaged, strata with weak reflectors. The three dimensional survey turned out to be problematic with many hyperbolic re_ectors that the seismic interpretation software could not handle. However, a few of the thirteen total lines collected showed similar characteristics as the two dimensional surveys. The sporadic local occurrence but consistent up-ice dipping reflectors within these closely collected transects are consistent with the deposition of imbricated packages of sediment on the stoss side of the forms.

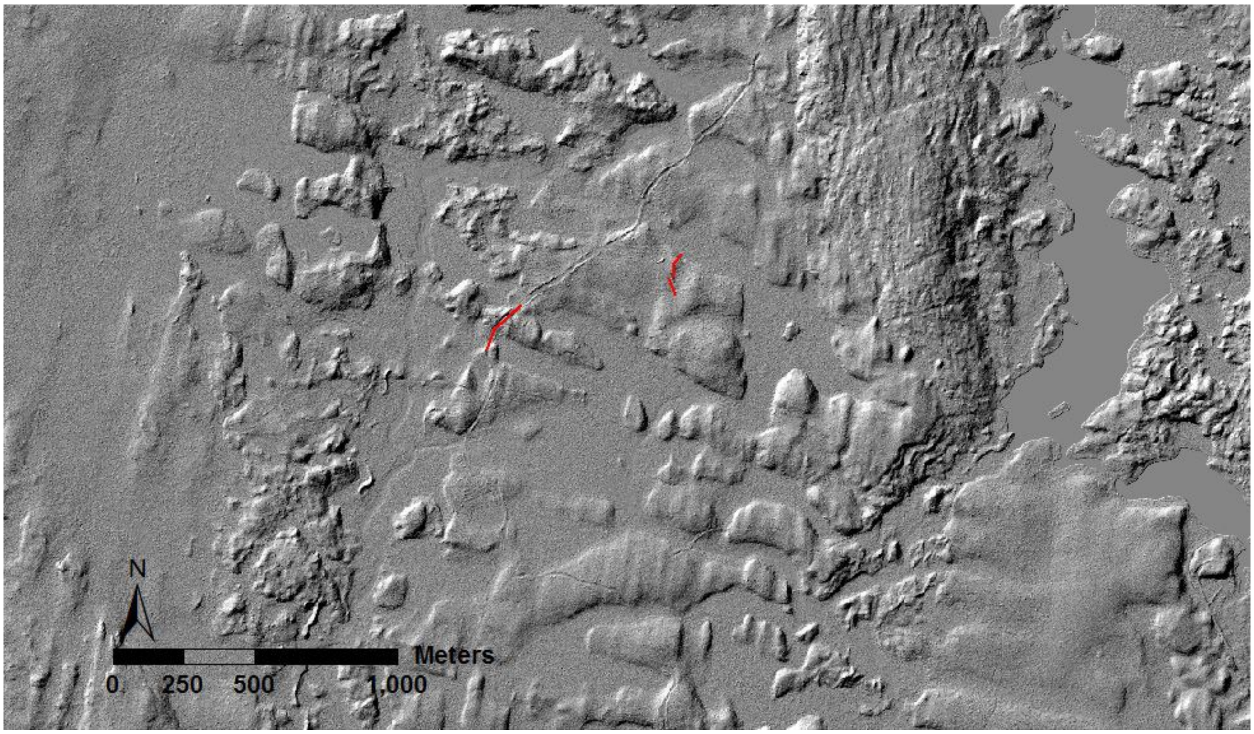

Figure 5 - Lidar image of Rögen moraine formed near scoured bedrock. Red lines indicate where two dimensional GPR scans were conducted. The transect labeled A corresponds to A in Figure 9.

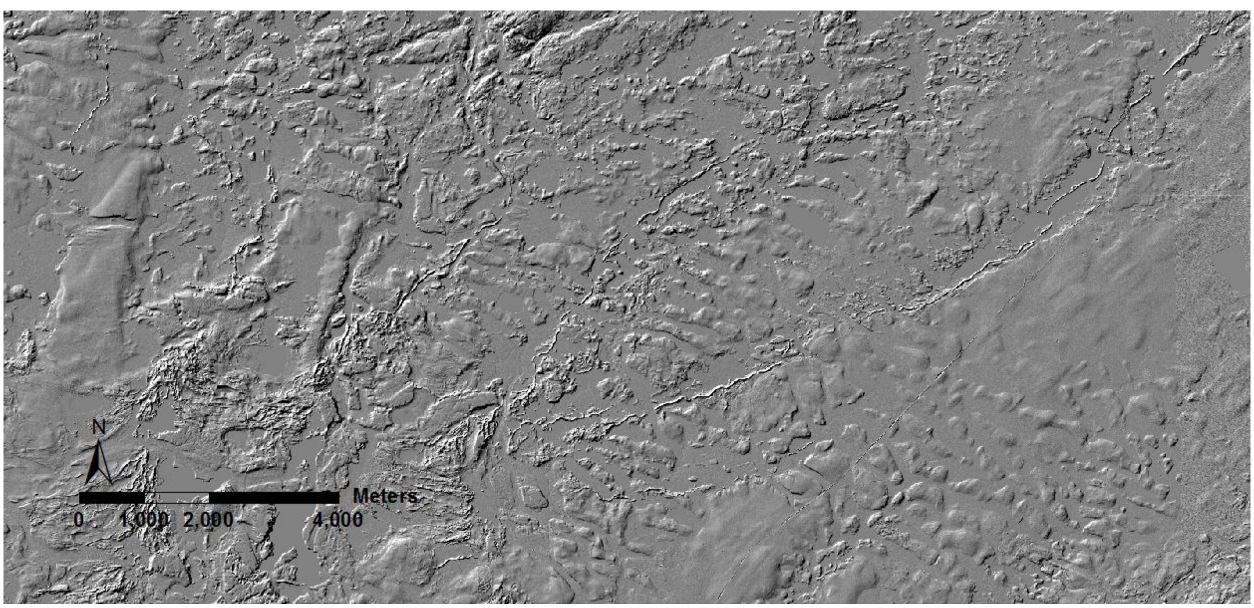

Figure 6 - LiDAR image of Rögen moraine forming at the transition from scoured bedrock to the north and drumlinized till to the south. On the western side of the image is ribbed moraine forming as part of a continuum with a drumlinoid feature. Eskers cross-cut the landscape and in some areas are deposited directly on bedrock. The outlined region represents location of the inset image. Red lines in inset LiDAR image illustrate location of GPR transects. Labeled red lines corresponed to transects shown in Figure 9.

6. Glaciological Model

Theories of Rögen moraine genesis typically use a change of velocity as the glaciodynamic mechanism for till sheet deformation. This is particularly true in extensional hypothesis where an apparent acceleration in ice sheet sliding velocity occurs via transition from frozen to thawed basal conditions (Hättestrand and Kleman, 1999). However, our hypothesis of velocity increase corresponds to the changing of glaciodynamic regimes. To test this, we generated a conceptual glaciological model that predicts ice sheet thickness using a predetermined accumulation pattern and basal shear stress.

Consider a flow line along the axis of the Rainy lobe. The _ow line is 1500 km long, from Hudson Bay to Central Minnesota and the Equilibrium Line Altitude (ELA) is 300 km from the ice margin. Maximum positive net balance is 800 kg m-2 yr-1 100 km up glacier from the ELA and decreases toward the ice divide to 500 kg m-2 yr-1. Therefore net balance for the accumulation area is given by

$$Bn_{acc} = \int_0^{1100} 2.73 \cdot 10^{-4}\mathbf{x} + 500\,\mathbf{dx} + \int_{1100}^{1200} -0.008\mathbf{x}\,\mathbf{dx} \ .$$

Assuming the Rainy lobe to be in balance, we get the net balance for the ablation area to be

$$Bn_{acc} = Bn_{\text{ab}} = -m\int_{1200}^{1500} x\,\mathbf{dx} \ .$$

Using the above net balance equations to determine the ice _ux, Glen's Flow Law

$$\dot{\varepsilon}_{\mathrm{yx}} = \left(\frac{\tau_{\mathrm{yx}}}{B}\right)^{\mathrm{n}}$$

where $\dot{\varepsilon}_{yx}$ is the strain rate, *B* is the ice viscosity of ice, τ_{yx} is the basal shear stress, given by,

$$\tau_{\mathrm{yx}} = \rho g h S$$

where ρ is the density of ice, *g* the acceleration of gravity, *h* the ice thickness, and *S* is the surface slope, can be integrated to estimate velocity as follows as

$$q = \int_0^H u(y)dy = \int_0^H \left(\frac{2}{N+1}\left(\frac{\rho g S}{B}\right)^3 y^{n+1}\right)dy$$

And

$$q = u_s H - \frac{2}{(n+1)(n+2)}\left(\frac{\rho g S}{B}\right)^3 H^{n+2}$$

Where *q* is the ice flux, *u(y)* is the velocity with depth below the surface, and *us* is the surface velocity.

To test our hypothesis of velocity increasing due to the transition from bedrock to till, we used a basal shear stress of 30 kPa in scoured bedrock terrain, and 20 kPa in regions of till. Within the 50 km transition zone where Rogen moraines are extensively distributed, an incremental stepping down in basal shear stress is used.

The model conceptually explains that the Rainy Lobe is experiencing acceleration along the flow line on the order of 30% to no more than 70% in the vicinity of bedrock to till transition. Acceleration at the transition will result in a raised sediment flux capacity causing advancement of hard bedded conditions as incoming sediment starved ice begins to carry sediment down ice.

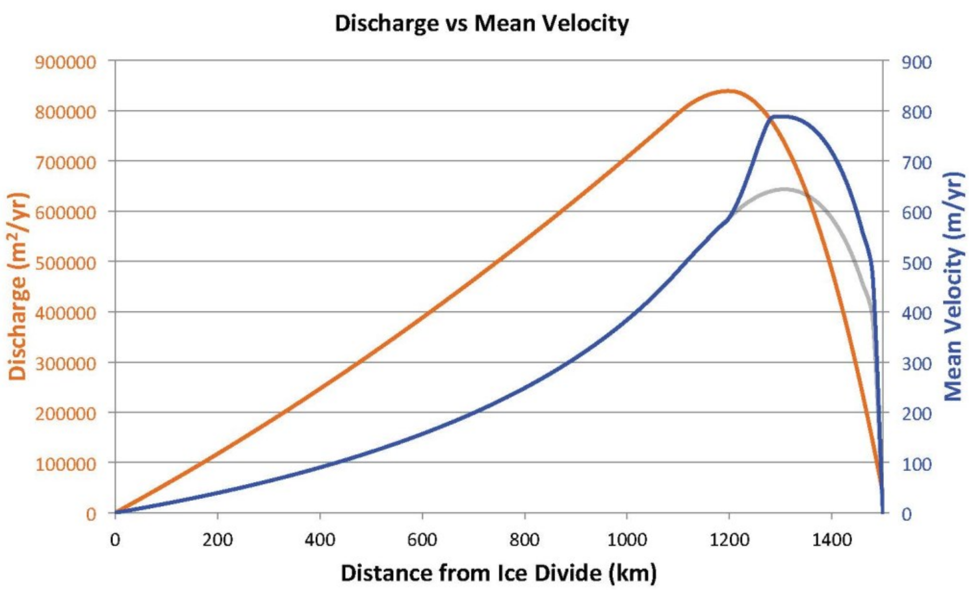

Figure 7 - Graph comparing discharge (m2 yr-1) and mean sliding velocity (m yr-1) of the Rainy Lobe along a flow line. The graph predicts ice acceleration in the region of basal shear stress reduction. The gray line is mean sliding velocity without the triggered acceleration from a decrease of basal shear stress.

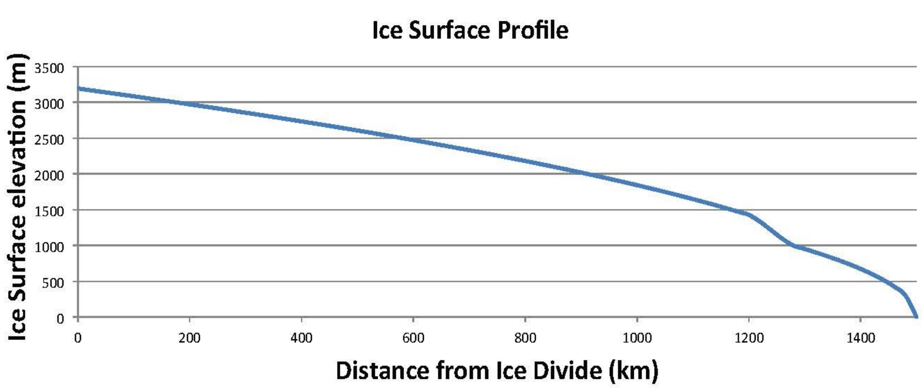

Figure 8 - Graph of predicted ice surface elevation of the Rainy Lobe, LIS. The Rainy Lobe thins in the region of reduced basal shear stress as an attempt to remain in balance with the thick, slow ice behind, resulting in divergent flow.

7. Results: Support for Fracturing Model

Hättestrand and Kleman (1999) propose that models of Rögenmoraine formation be compatible with, and able to explain, fourteen observations they described. They concluded that fracturing of a preexisting subglacial till sheet due to accelerating (divergent) iceflow at the transition from frozen (hard) to melting (soft) basal conditions, in juxtaposition with competent and incompetent materials best explains their observations. Our formation hypothesis is consistent with the fracturing mechanism in that ice is accelerating from decreased basal shear stress. However, the Minnesota examples lack a continuous till sheet. The striated bedrock, the up-ice-dipping re_ectors (possibly glaciotectonic structures) within the ribbed moraines, and the drumlins form a continuum. In contrast to Hättestrand and Kleman's (1999) model, northeastern Minnesota Rögen did not form in proximity to frozen substrate at the interior of the LIS. Rather, they formed proximal to the ice margin, in close spatial and temporal association with subglacial meltwater channels. We suggest that Hättestrand and Kleman's (1999) frozen-thawed Rögen formation model can be more generally restated that Rögen may form anywhere there is a transition from high basal shear stress to low basal shear stress environments where there is available sediment.

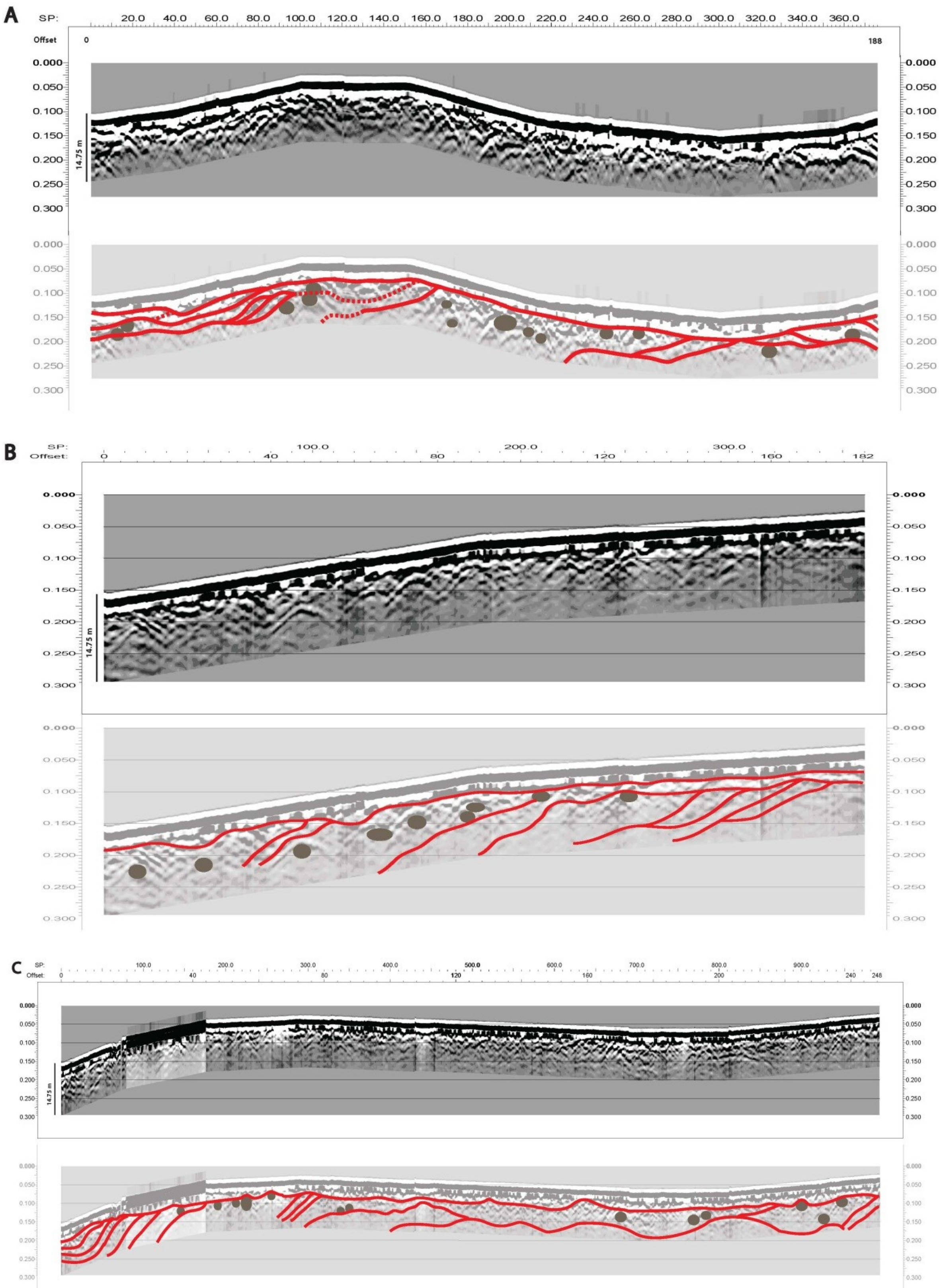
A
SP:
Offset
14.75 m
B
SP:
Offset:
14.75 m
C
SP:
Offset:
14.75 m

Figure 9 - Presentation plots of topography corrected Ground-penetrating Radar transects paired with interpreted illustrations. In all plots ice flow line is from left to right. Red lines are interpreted reflectors; dashed lines indicated approximate or assumed reflectors. Tan-gray ellipses indicate location of hyperbolic re_ectors interpreted to be boulders. Each sub-figure has its own scale bars. Horizontal scale shows location of shotpoints with offset in meters. Vertical scale is in seconds. Each transect and interpreted section is labeled with a letter that corresponds to same labeled transect in either Figure 5 or Figure 6, respectfully. A) Transect is 188 meters long. In this section we observed imbricated up-ice dipping reflectors on the stoss side of the form prior to Rögen crest and anastomosing subhorizontal reflectors throughout the transect. B) Transect is 182 meters long. This is the same Rögen scanned previously by a UMD graduate student, Margretta Meyer, whom this project is continued work after. In this transect we interpreted up-ice dipping re_ectors with imbricated structures. C) Transect is 248 meters long. The o_ colored section between shotpoints 80 and 175 is a result of a negative image – the contrast has been reversed. We interpreted many up-ice dipping reflectors on the stoss side of the form as we gathered on the uphill slope of the form. Coherent units defined by anastomosing subhorizontal reflectors are interpreted to be through much of the landform.

References

Bouchard, Michel A. (1989). Subglacial landforms and deposits in central and northern Québec, Canada, with emphasis on Rogen Moraines. *Sedimentary Geology*, 62(2), 293-308.

Clark, C D. (1999). Glaciodynamic context of subglacial bedform generation and preservation. *Annals of Glaciology, 28*(1), 23-32.

Clark, C. D.; & Meehan, R. T. (2001). Subglacial bedform geomorphology of the Irish ice sheet reveals major configuration changes during growth and decay. *Journal of Quaternary Science, 16*(5), 483-496.

Dunlop, P.; & Clark, C. D. (2006). The morphological characteristics of ribbed moraine. *Quaternary Science Reviews, 25*(13-14), 1668-1691.

Hättestrand, Clas. (1997). Ribbed moraines in Sweden: Distribution pattern and Palaeoglaciological implications. *Sedimentary Geology, 111*(1-4), 41-56.

Hättestrand, Clas; & Kleman, Johan. (1999). Ribbed moraine formation. *Quaternary Science Reviews, 18*(1), 43-61.

Larson, Phillip Christopher. (2008). Sediment transport cycles of the Laurentide ice sheet. In *Quantification of glacial sediment erosion, entrainment, and transport processes and their implications for the dynamic history of the Laurentide ice sheet* (Unpublished doctoral dissertation). University of Minnesota. URL: http://www.d.umn.edu/dees/research/thesis/larson_thesis.pdf

Lehr, James David. (2000). *Pleistocene geology of the embarrass area, St. Louis County, Minnesota*. (M.S. thesis). University of Minnesota Duluth.

Lundqvist, Jan. (1969). Problems of so-called Rogen moraine. *Sveriges Geologiska Undersökning Ser. C*, 648.

Lundqvist, Jan. (1989). Rogen (ribbed) Moraine—identification and possible origin. *Sedimentary Geology, 62*(2-4), 281-292.

Lundqvist, Jan. (1997). Rogen Moraine -- an example of two-step formation of glacial landscapes. *Sedimentary Geology, 111*(1-4), 27-40.

Möller, P. (2006). Rogen Moraine: an example of glacial reshaping of pre-existing landforms. *Quaternary Science Reviews, 25*(3-4), 362-389.

Roy, M.; Clark, P. U.; Barendregt, R. W.; Glasmann, J. R.; & Enkin, R. J. (2004). Glacial stratigraphy and Paleomagnetism of late Cenozoic deposits of the north-central United States. *Geological Society of America Bulletin, 116*(1), 30-41. URL: http://www.geo.oregonstate.edu/files/geo/Royetal-GSAB-2004.pdf

Sutinen, Raimo; Jakonen, Mari; Piekkari, Matti; Haavikko, paula; Narhi, Paavo; Middleton, Maarit. (2010). Electrical-sedimentary anisotropy of Rogen moraine, lake Rogen area, Sweden. *Sedimentary Geology*, 232(3), 181-189.

Acknowledgements

Special thanks to all the field assistances who helped with GPR data acquisition: Kirk Wyman, Evan Finnes, Chad Nogosek, and Jeffery Harrison; and, thanks to Nigel Wattrus for his assistance with data processing. We would also like to thank the Natural Resource and Research Institute for their generous donation of a vehicle.

Project Faculty Adviser:
Dr. Howard D. Mooers, Department of Earth and Environmental Sciences, Swenson College of Science and Engineering, University of Minnesota Duluth. Email: hmooers@d.umn.edu